

FINAL REPORT

STUDIES OF MARTIAN POLAR REGIONS

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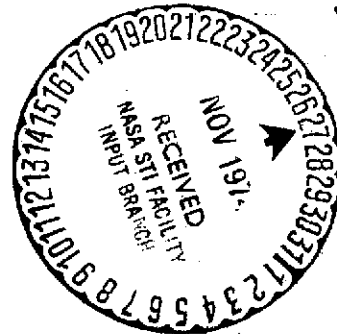
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## SUMMARY AND CONCLUSIONS

The studies of Martian Polar Regions involved two relatively independent studies. The first was carried out by Mr. David Nash under the general direction of Drs. Smith and Eschman, and consisted of a computer analysis of shapes of the low-albedo markings on the polar caps. The intention was to test hypotheses for the origin of the features as either constructional, as suggested by Murray and Malin, or erosional, as advanced by Cutts.

Nash showed that the degree of regularity of the markings did not vary from "oldest to youngest", as might have been expected if the markings were the edges of plates piled one on top of another. If the constructional hypotheses were correct, the markings at the edge of the "youngest" plate could be expected to be either less regular or more regular than the old margins which had been exposed to Martian surface processes for a long time. Nash concluded that the markings were more likely to be erosional.

The second study was carried out by Ms. Rosemary Mullin and Dr. Clark and consisted of a series of compressional deformation experiments on solid CO<sub>2</sub> to investigate whether CO<sub>2</sub> could have been an active glacial agent at the Martian poles. In the period of the grant, they built and tested a device for low temperature tests, and completed a set of experiments at 1 atmosphere confining pressure.

Mullin and Clark showed that CO<sub>2</sub> has a strength between  $\frac{1}{10}$  and  $\frac{1}{4}$  the strength of water ice near their respective melting points. They concluded that although flow may not be occurring at the present time, a glacial model for the origin of the unique polar topography and layered deposits was a realistic model and should

be considered an alternative working hypothesis.

The details of both studies are included in Appendices II and III in the form of manuscripts submitted for publication.

## Project Status and Future Work

The study of the polar regions should not be considered completed, but we are at a logical stage for deciding what, if any, further stages are worth undertaking. The following is an attempt to evaluate future courses of action. Since the study of the regularity of markings is complete I (BRC) will concentrate on the flow law studies.

Two important questions remain to be answered in the flow law study. The first is whether there is any pressure effect on strength. This can only be done by carrying out the experiments at high confining pressure. Although the equipment now exists to carry out these experiments, some developmental work remains. Coupled with this question is the effect of temperature close to the melting point, as opposed to the sublimation point. To stabilize temperature more carefully, a slight apparatus change should be made, but it is not a major additional project.

The fundamental decision to be made is whether further refinement of the flow law is worth the effort expended. We now have a reasonably accurate picture of how CO<sub>2</sub> is going to behave, and it is unlikely that our picture will change dramatically with this next stage of work.

My recommendation is to postpone any further work until the general response to the concept of CO<sub>2</sub> glaciation is known. If convincing observational arguments against the hypothesis are voiced, then the work would be superfluous. On the other hand, if the hypothesis remains viable, then the further studies surely should be undertaken, and I would be happy to direct further work on the problem. Such a decision should be made in time for inclusion in the budget for fiscal year 1976. In the meantime the attached paper will be circulated internally and submitted for publication.

## Personnel

The following people were directly involved in bringing the project to completion:

### Faculty

Professor Charles I. Smith

Associate Professor Bruce R. Clark

Professor Donald F. Eschman

### Graduate Students

Mr. David Nash

Ms. Rosemary Mullin

Mr. Christopher Drexler

Mr. Joseph Bailly

## Theses and Publications

Nash, David, 1973, The relative age of the escarpments in the Martian polar laminated terrain based on morphology: M.S. Thesis,

Ann Arbor, The University of Michigan, 31 p.

✓ Nash, David, 1974, The relative age of the escarpments in the Martian polar laminated terrain based on morphology: Icarus, 22:385-96.

Mullin, R.R., 1974, The deformation of solid carbon dioxide:

M.S. Thesis, Ann Arbor, The University of Michigan, 31p.

Clark, B.R. and Mullin, R.P., 1974, Martian glaciation and the flow of CO<sub>2</sub> ice (abst.): EOS, v.55, p.342.

✓ Clark, B.R. and Mullin, R.P., 1974, Martian glaciation and the flow of solid CO<sub>2</sub>: in prep.

DSIGNON CBVC T=10 P=30 COPIES=2 'DAVID NASH'  
 JOB-TYPE=BATCH, PRIO=NORMAL, CLASS=UNIV/GOVT

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USER "BOBVC" SIGNED ON AT 12:53.58 ON TUE NOV 19/74

BCOPY \*SOURCE\* -A

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BCOPY \*SOURCE\* -C

BLIST -A

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1      DIMENSION XLOC(150),YLOC(150)
2      READ (4,10) VANG,RANGE,ENFAC,X,Y
3      10  FORMAT (F7.3,F6.0,F6.2,2F5.2)
4      A=57.29576
5      VANG=VANG/A
6      THETA=90./A-VANG
7      H=RANGE*COS(VANG)
8      ROTC=-(59.+(39.+20./60.)/60.)/A
9      GAMMA=50.*(12.5/832.)/ENFAC
10     F=5.2267
11     20  READ (5,30,END=80) NUM,J
12     30  FORMAT (2I3)
13     READ (5,40) (XLOC(I),YLOC(I),I=1,NUM)
14     40  FORMAT (10F5.2)
15     DO 50 I=1,NUM
16     XT=XLOC(I)
17     YT=YLOC(I)
18     YLOC(I)=((YT-Y)*COS(ROTC)-(XT-X)*SIN(ROTC))*GAMMA
19     XLOC(I)=((XT-X)*COS(ROTC)+(YT-Y)*SIN(ROTC))*GAMMA
20     PHI=ATAN(YLOC(I)/F)
21     XLOC(I)=XLOC(I)*H*COS(PHI)/(F*SIN(THETA+PHI))
22     YLOC(I)=SIN(PHI)*RANGE/SIN(THETA-PHI)
23     50  CONTINUE
24     WRITE (6,60) NUM,J
25     60  FORMAT (2I3)
26     WRITE (6,70) (XLOC(I),YLOC(I),I=1,NUM)
27     70  FORMAT (10F3.2)
28     GO TO 20
29     80  STOP
30     END

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BLIST -B

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1      DIMENSION X(150),Y(150),ANG(150)
2      10  READ (5,20,END=60) NPNT,NFEA
3      20  FORMAT (2I3)
4      READ (5,30) (X(I),Y(I),I=1,NPNT)
5      30  FORMAT (10F3.2)
6      N=NPNT-1
7      DO 40 J=1,N
8      K=J+1
9      IF (X(K)-X(J).EQ.0.) X(J)=X(J)+.0001
10     IF (Y(K)-Y(J).EQ.0.) Y(J)=Y(J)+.0001
11     TANG=ATAN(ABS(X(K)-X(J))/ABS(Y(K)-Y(J)))*57.29576
12     IF (X(K)-X(J).GT.0..AND.Y(K)-Y(J).GT.0.) ANG(J)=TANG
13     IF (X(K)-X(J).GT.0..AND.Y(K)-Y(J).LT.0.) ANG(J)=180.-TANG
14     IF (X(K)-X(J).LT.0..AND.Y(K)-Y(J).LT.0.) ANG(J)=180.+TANG
15     IF (X(K)-X(J).LT.0..AND.Y(K)-Y(J).GT.0.) ANG(J)=360.-TANG
16     40  CONTINUE
17     WRITE (6,20) NPNT,NFEA

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18 WRITE (6,50) (ANG(I),I=1,N)
19 50 FORMAT (10F8.3)
20 GO TO 10
21 60 STOP
22 END
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BLIST -C

```

1 DIMENSION X(150),Y(150),ANG(150),RANG(150),SIZE(150)
2 WRITE (6,1)
3 1 FORMAT ('1',6X,'NUMBER OF FEATURE',11X,'NUMBER OF POINTS',10X,'A
4 LARGE LINE SEGMENT',6X,'AVERAGE ANGLE/KM.',7X,'SAMPLE VARIANCE OF
5 WRITE (6,2)
6 2 FORMAT (' ',31X,'COMPRISING THE FEATURE',11X,'LENGTH (KM.)',36X
7 THE ANGLE/KM.')
8 WRITE (6,3)
9 3 FORMAT ('-')
10 10 READ (5,20,END=90) NPNT,NFEA
11 20 FORMAT (2I3)
12 N=NPNT-1
13 READ (4,30) (ANG(I),I=1,N)
14 30 FORMAT (10F8.3)
15 READ (5,40) (X(I),Y(I),I=1,NPNT)
16 40 FORMAT (10F8.2)
17 ASIZE=0.
18 DO 50 K=1,N
19 SIZE(K)=SQRT((X(K+1)-X(K))**2+(Y(K+1)-Y(K))**2)
20 ASIZE=ASIZE+SIZE(K)
21 50 CONTINUE
22 ASIZE=ASIZE/(NPNT-1)
23 N=NPNT-2
24 AANG=0.
25 DO 60 I=1,N
26 RANG(I)=(ANG(I+1)-ANG(I))/(SIZE(I+1)+SIZE(I))
27 AANG=AANG+RANG(I)
28 60 CONTINUE
29 AANG=AANG/N
30 VAR=0.
31 DO 70 L=1,N
32 VAR=VAR+(RANG(L)-AANG)**2
33 70 CONTINUE
34 VAR=VAR/N
35 WRITE (6,80) NFEA,NPNT,ASIZE,AANG,VAR
36 80 FORMAT (' ',13X,I3,24X,I3,24X,F6.3,18X,F7.3,18X,F7.4)
37 GO TO 10
38 90 WRITE (6,100)
39 100 FORMAT ('1')
40 STOP
41 END

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## APPENDIX 11

The Relative Age of the Escarpments in the Martin Polar Laminated Terrain  
Based on Morphology

by David B. Nash

Department of Geology and mineralogy, University of Michigan Ann Arbor, Michigan

## APPENDIX 11

MARTIAN GLACIATION AND THE FLOW OF SOLID CO<sub>2</sub>

Bruce R. Clark  
Rosemary P. Mullin

Department of Geology & Mineralogy,  
The University of Michigan,  
Ann Arbor, Michigan, 48104.



ABSTRACT

The flow law determined experimentally for solid CO<sub>2</sub> establishes that an hypothesis of glacial flow of CO<sub>2</sub> at the Martian poles is not physically unrealistic. Compression experiments carried out under 1 atmosphere pressure and constant strain rate conditions demonstrate that the strength of CO<sub>2</sub> near its sublimation point is considerably less than the strength of water ice near its melting point. The data fit a power law 'creep' equation of the form:

$$\dot{\epsilon} = 4 \times 10^6 \cdot \sigma^{3.9} \cdot e^{-\frac{12,200}{RT}}$$

where  $\dot{\epsilon}$  is the compressive strain rate,  $\sigma$  is the compressive stress, R is the gas constant in calories per mole, and T is the absolute temperature. The exponent of  $\sigma$  of 3.9 contrasts with a value near 3.1 for water ice, and indicates that the strain rate is somewhat less sensitive to stress for CO<sub>2</sub> than for water. Likewise, the low activation energy for creep, 12,200 cal/mole, means that CO<sub>2</sub> is not highly sensitive to temperature and is thus likely to flow over a broad range of temperatures below its melting point. Actual strength values for CO<sub>2</sub> are on the order of  $\frac{1}{10}$  to  $\frac{1}{4}$  of the strength of ice under equivalent conditions.

A plausible glacial model for the Martian polar caps can be constructed and is helpful in explaining the unique character of the polar regions. CO<sub>2</sub> deposited near the pole would have flowed outward laterally to relieve high internal shear stresses. The topography of the polar caps, and the uniform layering and general extent of the layered deposits could all be explained using this model. The flow of CO<sub>2</sub> rather than water greatly reduces the problems with Martian glaciation. Nevertheless problems do remain, in particular the large amounts of CO<sub>2</sub> necessary, the need to increase vapor pressure and temperature with depth in the polar deposits, and the lack of good observational evidence of flow features.

Within the limits of the present knowledge of Mars, CO<sub>2</sub> glaciation appears to be a realistic alternative working hypothesis for the origin of the polar features.

## INTRODUCTION

Major topographic and sedimentary features found at both poles on Mars appear similar to those features associated with glaciated terrain on earth. In particular, each of the Martian poles is covered by deposits of surficial material whose surface is marked by a lobate pattern of topographic relief centered near the planet's axis of rotation. In addition, a mantle of surficial deposits, perhaps as much as 5-10 km thick at its center, blankets both polar regions and generally becomes thinner away from the poles (Murray, et al, 1972; Cutts, 1973b). Finally, large permanent ice caps still exist at both poles, and significant amounts of additional frozen volatiles may be present in the layered deposits which extend for hundreds of kilometers beyond the caps themselves.

Nevertheless, glacial origins for these unique polar features on Mars have been virtually completely discounted, largely on the basis of our understanding of the flow properties of water ice (Sharp, 1974). For example, present surface temperatures are far too low to allow water ice to flow appreciably. Furthermore, the reduced gravity requires enormous thicknesses of ice for flow to begin, and yet little free water has actually been found on the Martian surface. Also, Mariner 9 photographs revealed craters which have been interpreted (Murray, et al, 1972) to be exhumed from beneath layered deposits but show no evidence of modification or erosion from flow in the overlying deposits. If this interpretation is correct, then glaciers as we see them on earth could hardly have flowed across the Martian polar surface.

The difficulties with water ice as a glacial agent on Mars led the authors to examine the flow behaviour of solid CO<sub>2</sub>. CO<sub>2</sub> is an obvious choice for a

possible glacial agent on Mars. It is not only the most abundant volatile now found at the planetary surface, but temperatures at both poles are presently such that any near-surface  $\text{CO}_2$  is close to its sublimation point and thus likely to be weak and ductile in the Martian polar environment. Furthermore, terrestrial thermal gradient on Mars could bring a deposit of  $\text{CO}_2$  close to, and perhaps above its melting point at depth (Sagan, 1973).

The authors have therefore derived a flow law for solid  $\text{CO}_2$  from a series of laboratory deformation experiments. The flow law can be used to predict the behaviour of  $\text{CO}_2$  under conditions generally accepted for the present Martian polar regions. Because the strength of  $\text{CO}_2$  near its sublimation point is significantly less than that of water near its melting point (Glen, 1955), it is not yet possible to eliminate the hypothesis that the unique features found near the Martian poles are the result of, or at least have been strongly influenced by a type of glacial flow in which  $\text{CO}_2$  is the dominant flow medium. Consequently, we speculate on a plausible  $\text{CO}_2$  glacial model and on the constraints required by such a model.

## Experimental Procedure

The Flow Law for  $\text{CO}_2$  was derived from sets of compression experiments at 1 atmosphere confining pressure, constant strain rate, and temperatures from 163° to 193°K. Jacketed samples of solid  $\text{CO}_2$  19mm in diameter by 48mm long were compressed axially in an insulated chamber cooled by liquid nitrogen (Fig. 1). Temperature gradients along the sample were kept to less than 3°K by cooling the upper and lower halves of the chamber independently. However, thermal drift of the unit as a whole was difficult to control for long periods of time. As a result, the experiments were terminated after strain of a few percent or less, but in each case, not until the stress-strain curves had become essentially flat. The evidence from a few extended tests indicated that strain hardening did not affect the strength values greatly, within the temperature and strain rate ranges used here.

The  $\text{CO}_2$  samples were cored from large blocks of commercially prepared solid  $\text{CO}_2$ . The blocks are formed converting liquid  $\text{CO}_2$  to snow at low temperature, then compacting the snow under pressures as high as 150 bars. Minute amounts propylene glycol (.02%) and oil (.001%) are added to the  $\text{CO}_2$  snow to increase the adhesion between grains, but the only other measurable impurity is a trace of water. The starting material has a texture of interlocked equidimensional grains of very uniform grain size, approximately 0.3mm in diameter. Grain boundaries are smooth and simple. No pore spaces are visible even under magnifications of 40x.

The authors did not attempt to investigate any of the  $\text{CO}_2$  clathrate compound suggested by Miller and Smythe (1970) as present in the Martian polar caps. Sharp (1974) assumes that only minor amounts of clathrate would be present, limited by an apparently severe shortage of available  $\text{H}_2\text{O}$ . The composition of volatile layers beneath the surface of the polar cap remains open for speculation.

# FLOW LAW FOR CO<sub>2</sub>

The results of the deformation experiments are plotted in Figure 2 as a graph of the log of strength ( $\sigma$ ) vs. the log of the strain rate ( $\dot{\epsilon}$ ) for a series of different temperatures. When plotted using these coordinates, the data for a single temperature appear to lie approximately along a straight line, although the range and accuracy of the points are not great enough to establish such a power-law relationship as the best-fitting law possible (see also Sherby and Burke, 1967). There is some suggestion from the 188° data that the straight-line relationship does not hold. However, at other temperatures the fit is quite good, and the assumption of a power-law fit seems justified for extrapolation over only two orders of magnitude to hypothetical glacial strain rates ( $10^{-9}$ /sec).

The fit of straight lines by least squares to all points for each temperature gives a relationship:

$$\log \dot{\epsilon} \propto N \log \sigma$$

where N varies between 3.0 and 4.9 with a mean value of 3.9. The scatter of N is not temperature dependent and should be reduced if an expanded range of strain rates were tested. This contrasts with values of N for water ice found from creep tests (Glen, 1955) and from tunnel closure measurements (Nye, 1953) of 3.17 and 3.07 respectively. Thus the strength of CO<sub>2</sub> is somewhat less sensitive to strain rate than the strength of water ice.

The effect of temperature on CO<sub>2</sub> strength is assumed to be of the commonly used form (Sherby and Burke, 1967):

$$\dot{\epsilon} \propto \exp(-Q_c/RT)$$

where  $Q_c$  is the activation energy for creep. A plot of  $\log \dot{\epsilon}$  vs.  $1000/T$  is shown in Figure 3 in which the slope of the line has the value

$$Q_c/2.3 \times 10^3 \times R$$



The value of  $Q_c$  is found to be 12.2 Kcal/mole from the experimental results.

The activation energy for creep can commonly be correlated with activation energies for self diffusion of atomic or molecular species, but to our knowledge no appropriate diffusion measurements have been made on solid  $CO_2$ . The creep activation energy for  $CO_2$  is considerably smaller than that for water ice, given by Glen (1955) as 31.8 Kcal/mole. Thus the strength of  $CO_2$  is less affected by differences in temperature than the strength of water ice.

The flow law for solid  $CO_2$  is thus found experimentally to be

$$\dot{\epsilon} = A \sigma^{3.9} \exp \left( \frac{-12.2}{RT} \right)$$

from which strength at an appropriate strain rate and temperature can be predicted, and general comparisons with the behaviour of water ice can be made (Fig.2).

An examination of the data in Figure 2 shows that at temperatures within a few degrees of the respective melting/sublimation points, water ice is considerably stronger than solid  $CO_2$ . At a strain rate of  $10^{-7}$ /sec  $CO_2$  is  $\frac{1}{5}$  as strong, and even with the steeper slopes of the  $CO_2$  lines it would still be less than  $\frac{1}{3}$  as strong at a strain rate of  $10^{-9}$ /sec.

If the pressure on buried  $CO_2$  rises to 5.1 bars (depth of burial of <100m), then the temperature is free to rise to 216°K before the solid becomes unstable (melts). Under those conditions the flow law would predict  $CO_2$  strengths lying along the dotted line to the left of the solid lines in Figure 2, giving a strength approximately  $\frac{1}{10}$  that of water ice under equivalent conditions. As discussed below, such a situation can easily arise at depth at the Martian poles if pressures can rise above 5 bars, and temperatures follow the planet's thermal gradient.

Extrapolation of the flow law to buried conditions requires that the flow law be independent of confining pressure. Rigsby (1958) showed that this was the case for water ice, and the flow laws for most other crystalline materials are also independent of confining pressure if brittle mechanisms are not active. No evidence of brittle mechanisms was observed in these experiments, either as stress drops in the bulk stress-strain curves, or in the form of microfractures which could be observed in the binocular microscope. The latter might be expected to appear as either discrete breaks between or across grains or as a clouding of individual grains if fracturing were submicroscopic; however, at 40x the grains appeared clear and unbroken. Nor was there any evidence, such as formation of visible porosity or opening of grain boundaries, that would indicate sliding had occurred along grain boundaries. Attempts to actually determine strengths under high confining pressures were postponed by difficulties with sealing the chamber at such low temperatures.

A second important assumption is that the proximity of the sublimation point to the experimental temperatures had no significant effect on the flow law. In other words, we presume that if we could raise the experimental temperature to the melting point ( $\sim 216^\circ\text{K}$ ) without sublimation taking place, the flow law would still remain valid. Good evidence to support this assumption is found in the excellent fit of the points to the constant  $Q_c$  line in Figure 3. Even within  $2^\circ\text{K}$  of the sublimation point, there is no suggestion that the activation energy is changed. Thus the flow law is assumed to be valid up to the melting point if sublimation can be eliminated, as it is at higher pressures.

One difficulty in evaluating these assumptions is our present lack of knowledge of deformation mechanisms in  $\text{CO}_2$ . The evidence that the material is deforming by intracrystalline mechanisms, probably translation gliding, is

primarily the lack of any features that appear to be due to cataclasis or brittle fracturing. Because of the face centered cubic structure of  $\text{CO}_2$ , the logical glide planes would be  $\{111\}$ , the closest-packed planes, and the glide direction  $\langle 1\bar{1}0 \rangle$ , which gives the shortest displacements. However, the arrangement of the elongate  $\text{CO}_2$  molecules in the structure results in complex interference between oxygen atoms during slip on these planes. This produces unknown effects on the Peierls energy, and we have as yet no optical evidence of that glide law.

DISCUSSION

The flow law for CO<sub>2</sub> clearly does not rule out the possibility that lateral flow of CO<sub>2</sub> may have occurred at the Martian poles and may be responsible for some of the unique surficial features. The strength of CO<sub>2</sub> under polar conditions could be as little as  $\frac{1}{10}$  the strength of water ice under glacial conditions on earth. Even the reduced gravity on Mars (370 cm/sec<sup>2</sup>) is partially offset by the higher specific gravity (1.5) of solid CO<sub>2</sub>. However, some critical requirements must be fulfilled if CO<sub>2</sub> can be expected to act as a glacial agent on Mars. These are considerably different from the requirements for water ice glaciation, and in the authors' opinion, much more likely to be met. Thus the establishment of the presence or absence of CO<sub>2</sub> flow would place some valuable new constraints on the Martian polar conditions. Unfortunately, although most investigators discount flow at the poles from Mariner 9 photographic studies (Murray, et al, 1972; Cutts, 1973; Sharp, 1974), alternate interpretations are possible (for example, by Sagan, 1973), and the matter remains unsettled.

For purposes of discussing the implications of a glacial mechanism the authors present a plausible model for a glacial origin of several of the important polar features observed on Mars. The model serves as an alternate hypothesis to the sedimentary and erosional models already suggested. Recognizing that our factual knowledge is limited, we see no compelling evidence that this model is the correct one. Nevertheless it is important that so long as alternative models are plausible, they not be dismissed. The flow behaviour of CO<sub>2</sub> suggests to us that strong arguments in opposition to water ice glaciation are not particularly valid for solid CO<sub>2</sub>, and thus the glacial origin of polar features is indeed reasonable.

### Plausible Glacial Model

The glacial model for the Martian poles is based on the assumption that a significant amount of CO<sub>2</sub> was once deposited in a thick pile at or very near the pole and flowed outward under its own weight. The general motion of this material would have been similar to the flow of the large Pleistocene ice sheets on earth, and the driving mechanism would have been an excess of internal shear stress over the long-term shear strength of CO<sub>2</sub>. The experimentally derived flow law for CO<sub>2</sub> guarantees that under the proper conditions, a thick deposit of CO<sub>2</sub> will flow laterally until it reaches a very thin "equilibrium" shape.

The concept of an equilibrium shape is borrowed from the physics of water-ice glaciers and was derived in a simplified form by Orowan (1949):

$$H = (Z T L / pg)^{\frac{1}{2}}$$

where H is the thickness of the sheet at its center, T is the shear strength, L is the half-width (nearly equivalent to the radius of a circular sheet), p is the density, and g is the gravitational attraction. A value of T can be estimated from the flow law, and we choose a conservatively large value of .2 bars at a strain rate of 10<sup>-9</sup>/sec, recognizing that

$$T = \sigma / \sqrt{3}$$

where  $\sigma$  is the compressive stress (Nye, 1953). Thus for a sheet of 1000 km radius on a flat base, the "equilibrium" thickness would be 2.6 km. There is of course no true equilibrium unless it could be shown that CO<sub>2</sub> has some fundamental strength. Nevertheless, as stresses decrease internally, the flow rate decreases to the level that the amount of flow is negligible. Cutts (1973b) suggests a maximum thickness of 6 km and an average thickness of 2 km as order-of-magnitude figures, in good agreement with the simplified calculation above. Adjustments can be made to the

"equilibrium" thickness by changing temperatures in the pile, or by assuming a depression in the underlying topography at the center of the sheet, etc. Without further information there is little point in artificially varying one or another parameter to attempt to fit Cutts' estimate more closely. The important point is that a lateral flow mechanism can account for the overall shape of the layered deposits quite effectively.

In the proposed model, CO<sub>2</sub> originally was deposited as a snow by the process envisioned by Cutts (1973b) in which both dust and volatiles were removed from the atmosphere. Layers of different albedo simply contain different proportions of dust and CO<sub>2</sub>. Once deposited, CO<sub>2</sub> began to convert to a metamorphic solid during burial, just as water snow is converted to ice in terrestrial ice sheets. Even though pressure melting is not an active process for CO<sub>2</sub>, the increasing temperature with depth would lead to recrystallization just as it does in the commercial preparation of CO<sub>2</sub>.

A periodic source for CO<sub>2</sub> seems to be required to produce the original layering at the poles. If the degassing of the planet was accomplished largely by intermittent volcanic emanations, the layered nature of the deposits is easily explained. Alternatively, CO<sub>2</sub> might have been accumulating continuously at the poles, but the supply of dust was limited to the times of volcanic activity.

As the thick deposit began to flow outward the topography of the surface reflected the unevenness of the flow beneath. Thus surging of the CO<sub>2</sub> sheet was accompanied by an uneven topographic surface which would eventually lead to the dark markings visible through the remnant polar caps. Although Cutts (1973a) supplies convincing evidence that wind erosion has had an important effect on the present relief of the polar cap, the interpretation of the dark markings as a spiral is certainly not a unique one. In the glacial model, the markings fit a

more nearly concentric lobate pattern about the poles, produced by low amplitude waves in the flow pattern of the underlying deposit. Either because of their presence as high points subjected to wind erosion, or the fact that the equator-facing slope received a higher level of insolation, the ridges were exposed and then incised to produce the visible markings. At present wind erosion is important, but its pattern is controlled largely by thermal contrast due to topographically controlled albedo differences.

The fact that thin layers are found even at the surface of the layered deposits, and just beneath the surface in the remnant polar caps (Murray, et al, 1972), suggests that the actual flow of CO<sub>2</sub>-rich layers had taken place at some time in the past when the present surface was buried. The evidence is strong against a present-day accumulation stage at either pole, so it seems likely the original deposit was somewhat thicker than the deposit we see now. Whether the material eroded away was CO<sub>2</sub>-rich as well, or was largely dust, is not known. Certainly the CO<sub>2</sub> in the present atmosphere seems insufficient to account for a thick missing sequence of CO<sub>2</sub>-rich layers.

Despite the similarity between the CO<sub>2</sub>glacial model and terrestrial ice sheets, the two can be expected to differ in some important ways. Since pressure melting does not occur, basal sliding would not be an important mechanism for movement of the sheet unless the thermal gradient were steep enough to cause melting at the base of the pile. Although this might be the case in the center of the deposit it does not seem likely where deposits are thinner. Consequently, features associated with movement of ice sheets on earth may not be present on Mars. These would include large terminal or recessional moraines, erosional features such as grooves or channels on the underlying surfaces, and of course the common outwash features.

Other hypotheses have been advanced to account for the origin of the polar features. In particular, Murray, et al (1972) suggested that the topography marked by the albedo differences on the polar cap was caused by escarpments at the edge of individual deposits of layered material. The deposits had the form of plates of decreasing size, at the south pole, while at the north pole they were slightly offset with respect to each other to give a spiral sequence of plates. Murray and Malin (1973a) attributed the offset to polar wandering. However, as Cutts (1973a) points out, the features at the north and south poles are not symmetric even though the wandering of the poles must be. Cutts (1973a) tentatively proposed that the dark markings on the cap are erosional, due to complexly circulating winds above the cap producing valleys or ravines in the surface. Thus he correlates a generally spiral pattern of markings, particularly at the north pole, with a spiral wind pattern blowing off the pole.

One difficulty with an erosional control for the dark markings is the lack of consistently spiral markings. At the south pole, the pattern is more concentric than spiral, and individual markings are discontinuous, and in some cases at high angles to other more general trends. Although complex wind patterns could certainly be present, it is difficult to imagine that deep erosion could be produced in such diverse directions.

Likewise the formation of layered deposits has been attributed to sedimentary processes in situ. Good arguments against glacial flow in these materials were summarised by Murray, et al (1972). They cited the lack of deformation of buried craters, the presence of outlying layered mesas and buttes separated from the rest of the layered deposits, and the lack of flow patterns in the layered deposits adjacent to craters over which they apparently flowed. In the CO<sub>2</sub> flow model, the buttes and mesas are simply the result of the present



erosional episode which has followed the glacial flow. The evidence for lack of erosion of underlying craters might be explained by the lack of basal sliding in the CO<sub>2</sub> flow model. Nevertheless the authors agree that some flow features should be found adjacent to the craters if the craters are in fact exhumed.

The sedimentation model has its own difficulties. To produce the original deposit, long period of quiet sedimentation, estimated as 10<sup>8</sup> years by Cutts (1973b), must have occurred with virtually no erosional episodes, since no features at all like the present topography are recorded in the layering. Furthermore, present photographs show no disruption of bedding by meteorite impacts. Although discussion of past conditions on Mars is highly speculative, such a long period of undisturbed subaerial deposition seems unlikely.

In summary, the glacial model explains a number of the most enigmatic features at the Martian poles. It accounts for the lobate dark markings on the permanent polar cap as the result of flow-derived topographic relief. It gives an estimate of the overall shape of the layered deposit sequence in terms of a reasonable shear strength for CO<sub>2</sub>. It predicts the remarkable regularity of the laminations in the layered deposits as a smoothing of much less regular original bedding by substantial lateral flow. Finally it might be possible to extrapolate the process to earlier times to account for the older surficial deposits underlying the layered deposits.

It appears that at present the factual evidence from observable features in the Mariner 9 photographs is not completely satisfactory for establishing one or another hypothesis as the true origin of the features. However, it is worthwhile to define the constraints on the physical conditions for CO<sub>2</sub> glaciation at the poles, and to consider whether these constraints are reasonable.

### Physical Constraints

The present Martian polar conditions are not ideal for the flow of  $\text{CO}_2$ , but with a few assumptions flow becomes a very tenable hypothesis. Most of these assumptions seem realistic, but it must be emphasized that they are required for the model to be acceptable.

The most difficult assumption is that there is or was enough  $\text{CO}_2$  at the Martian surface to produce a deposit the size of the present layered terrain composed of approximately 50%  $\text{CO}_2$ . Rough calculations by Cutts (1973b) of the volume of the layered deposits gave a value of  $5 \times 10^6 \text{ km}^3$ . Thus we might estimate the  $\text{CO}_2$  required as  $2.5 \times 10^6 \text{ km}^3$  or  $2.5 \times 10^{21} \text{ cm}^3$ . The present atmosphere of Mars contains about  $2 \times 10^{19} \text{ cm}^3$  (Murray and Malin, 1973b), so nearly 100 times as much solid  $\text{CO}_2$  would be stored in the layered deposits. Murray and Malin (1973b) make a convincing argument that a solid phase is present and controls the atmospheric pressure of Mars. They postulate a reservoir beneath the cap as much as  $10^{20} \text{ cm}^3$  based on the shape of an area beneath the North polar cap in which layered deposits may be absent. The glacial model would require that the amount of  $\text{CO}_2$  outgassing on Mars has been approximately  $1.5 \text{ kg/cm}^2$  of surface area as opposed to the  $60 \text{ g/cm}^2$  assumed by Murray and Malin. For comparison, the figure for earth is about  $70 \text{ kg/cm}^2$  (Murray and Malin, 1973b). While we see no violation of factual observation in this amount of outgassing, it clearly implies a significantly different history of differentiation and devolatilization than that of the Murray and Malin model.

A second important assumption is that burial can in fact cause the vapor pressure of  $\text{CO}_2$  to rise above 5mb. This seems to be quite a likely assumption and removes the thermal problems of  $\text{CO}_2$  storage in layered deposits implied by Murray and Malin (1973b). Because the equilibrium vapor pressure of  $\text{CO}_2$  is

extremely temperature dependent, an increase of pressure to 1 bar raises the sublimation temperature from  $150^{\circ}$  to  $195^{\circ}$ , well above any mean temperature for the regions containing the permanent caps. All that is required is a means of sealing the deposit. Although the dust layers themselves may act as a sealant, a second possibility would be a combination of dust,  $\text{CO}_2$  clathrate, and water ice. Even a small buildup of  $\text{CO}_2$  pressure at depth will stabilize the solid to much higher temperatures. Thus the presence of  $\text{CO}_2$  as a solid buried in the layered terrain is by no means impossible. However, that such a sealing action can occur in the materials that make up the layered deposit is still an assumption.

A further assumption is that the temperature increases with depth rapidly enough that most  $\text{CO}_2$  is near its melting point, even at the pole itself. The geothermal gradient for Mars is most likely positive with depth but the size of the gradient is not known. The presence of relatively young volcanic activity argues for a steep gradient. Sagan (1973) speculated that it might be equivalent to the earth's gradient,  $10\text{--}40^{\circ}\text{K/km}$ . Even a  $10^{\circ}$  gradient would bring  $\text{CO}_2$  near its melting point at the 6km depths postulated by Cutts (1973b). Higher gradients would in fact produce melting of  $\text{CO}_2$  at depth and as Sagan (1973) maintained, would probably limit the thickness of the deposit.

We conclude that the flow law for  $\text{CO}_2$  precludes significant flow of  $\text{CO}_2$ -rich layers in the  $150^{\circ}\text{K}$  conditions at the surface of the polar caps, but that under certain conditions, flow at depth in  $\text{CO}_2$ -rich deposits is indeed quite likely. A plausible model which explains several of the important features found in the polar deposits can be developed, but it is neither a unique glacial model, nor is there compelling evidence yet available that glaciation is the best way to explain the features. Several assumptions are inherent in the glacial model, and these assumptions imply new and different constraints from those of other hypotheses.

The authors urge that this and other models be retained as working hypotheses until proven invalid, and that care be taken in using constraints on atmospheric history or devolatilization of the planet based on one model.

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ILLUSTRATIONS

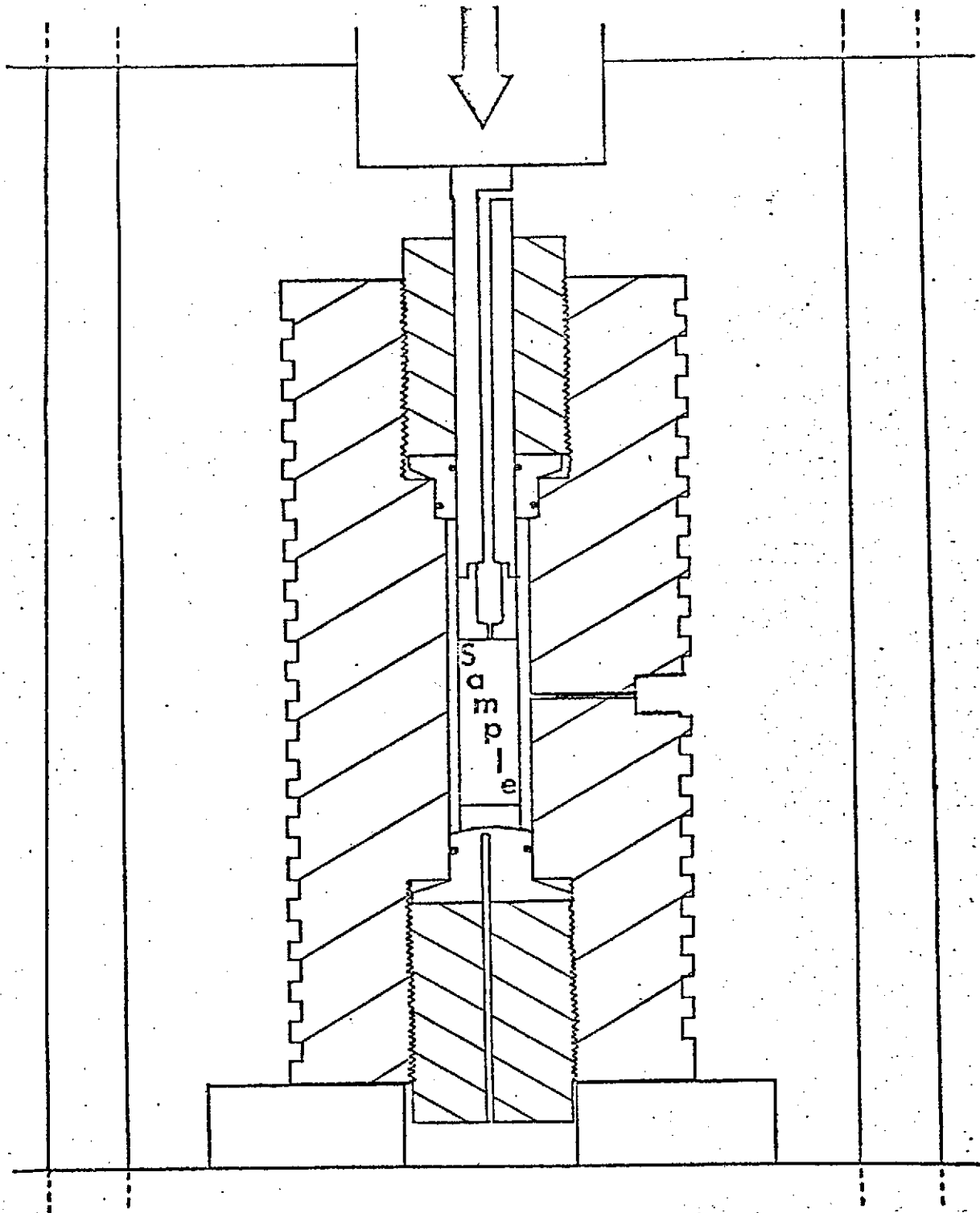
Figure 1. Schematic drawing of sample chamber in place within hydraulic press. Grooves on outside of chamber are pathways for liquid nitrogen coolant.

Figure 2. Strength of  $\text{CO}_2$  vs. strain rate data on which flow law is based. Solid lines are straight lines fit to data with slope of 3.9. Dotted line at left is extrapolation to melting point of  $\text{CO}_2$ . Dashed lines at right are data for water ice at temperature given (from Glen, 1955).

Figure 3. Strain rate vs.  $1000/T$  for a constant stress of 4 bars. Points marked with X are values determined from straight line in Figure 2. Point marked with O was used to produce dotted line in Figure 2.



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